Negative Photoconductivity Associated with Impurity Conduction in Germanium*

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Photoconductivity in germanium has been studied at temperatures and doping levels at which impurity conduction processes are important. Under certain conditions negative photoconductivity is observed. Results as a function of intensity and wavelength are explained by a simple model which is consistent with accepted views of impurity conduction.

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* This work supported in part by a grant from the National Aeronautics and Space Administration, Grant No. NSG-228-62.

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At low temperatures heavily doped germanium exhibits impurity conduction processes which depend sensitively on the concentration of donors (or acceptors) and on the compensation.[1/] Fritzsche[2/] has shown that these processes are characterized by activation energies which are clearly observed in log resistivity vs. reciprocal temperature plots. Figure 1 illustrates the behavior of n-type germanium with low compensation as the donor concentration is increased. The activation energy ϵ_1 is the familiar donor ionization energy which decreases with increasing N_D. In the low concentration range ($N_D < 10^{16}$ antimony atoms cm^{-3}) only one other activation energy ϵ_3 is apparent; it has been successfully interpreted[3/] as the energy associated with the transition by tunneling of an electron from an occupied to an unoccupied site. The existence of the latter presupposes some compensation and the activation energy arises because of the need to overcome the Coulomb potential associated with the compensating acceptor. As N_D is increased ϵ_3 at first increases and then decreases. In the intermediate concentration range ($2x10^{17} > N_D > 2x10^{16}$ Sb atoms cm^{-3}), another activation energy ϵ_2 appears in the curves. No single model has been agreed upon for the process characterized by ϵ_2 but its rapid decrease with increasing N_D suggests that it is controlled predominantly by the overlap between wave functions on neighboring donor sites. Fritzsche has suggested it is associated with excitation to a band formed by interaction between negatively charged donor sites. Support for this model has been obtained from studies of ϵ_2 as a function of compensation[4/] and as a function of stress.[5,6/] Theories based on the model have been developed by Mikoshiba[5] and Nishimura.[7] When N_D is $> 2 \times 10^{17}$ Sb atoms cm^{-3}, $\epsilon = 0$ and the resistivity becomes temperature independent below 10°K corresponding to the formation of an impurity band.

As the compensation $K = N_A/N_D$ is increased, ϵ_3 passes through a minimum value at K = 0.5 in the low concentration range[8] as predicted by theory[3] and at K < 0.5 in the intermediate concentration range.[4] The activation energy ϵ_2 increases with increasing K for all donor concentrations.[4]

In making measurements of the type described above it is normally essential to prevent any radiation from falling on the specimen. This is because of probable excitation of electrons into the conduction band, where they would have a sufficiently high mobility to mask completely the impurity conduction processes. Dobrego and Ryvkin[9] have reported, however, a negative photoconductivity in heavily doped samples at low temperatures which suggests rapid trapping of the photo-excited carriers. At higher light levels a positive photoconductivity resulted and evidently, under these conditions, sufficient free carriers were excited to the conduction band to control the conductivity.

The intensity dependence of photoconductivity in germanium samples at 4.2°K has been measured in this laboratory. Results using excitation of wavelength 1.5μ are shown in Fig. 2. In sample N1 containing 1.8×10^{16} Sb atoms cm^{-3} and P1 containing 3.7×10^{15} Ga atoms cm^{-3}, negative photoconductivity was observed at low intensities of illumination. Positive photoconductivity only was observed in sample N2 containing 7×10^{16} Sb atoms cm^{-3}.

Figure 3 shows the wavelength dependence of the negative photoconductivity in the first n-type sample for two arbitrary values of the intensity. It is clear that the effect arises only for excitation by light of energy greater than the band gap. The decrease of the effect at short wavelengths corresponds to a drastic decrease in the lifetime of the excited carriers as the excitation takes place predominantly near the surface.

For wavelengths less than about 3000 Å, an increase in conductivity which persisted after removal of the light was observed in all samples. No decay of this induced conductance was observed over many hours while the sample was maintained at a low temperature. Raising the temperature to that of liquid nitrogen and subsequently recooling restored the conductance to its original dark value. Surface trapping is thought to be responsible for this effect.

Figure 4 illustrates a model for the negative photoconductivity observed in samples N1 and P1. These specimen are in the low concentration range where the existence of vacant donor sites is necessary for impurity conduction. Figure 4a shows the situation in the dark at low temperatures; the number of vacant donor sites is equal to the number of acceptors. If, after excitation of electron-hole pairs (Fig. 4b), some of both kinds of carriers become trapped in the manner shown then there will be an effective decrease in the compensation; the number of vacant donor sites is decreased and the acceptors which trap holes become neutral. Impurity conduction in the donor levels is thereby reduced. At high light intensities the conduction by untrapped carriers predominates and normal positive photoconductivity is observed.

Evidence for the above interpretation was obtained by observing that the negative photoconductivity was associated with an increase in the activation energy ϵ_3 as predicted[3/] for a decrease of compensation in this range. Figure 5 shows results in specimen P2 which had a chemical compensation of 0.4.

Sample N2 (Fig. 2) is in the intermediate concentration range. The effect of decreasing the compensation in such samples is to decrease ϵ_2[4/] with an associated increase in the conductivity as observed.

REFERENCES

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FIGURE CAPTIONS

Figure 1 Variation of resistivity with temperatures for Sb-doped Ge (from Ref. 4). The dashed lines divide the regions characterized by activation energies ϵ_1, ϵ_2, and ϵ_3.

Figure 2 Photoconductivity associated with impurity conduction as a function of light intensity. Sample N1 contained 1.8×10^{16} Sb atoms cm^{-3}; sample P1, 3.7×10^{15} Ga atoms cm^{-3}; and sample N2, 7×10^{16} Sb atoms cm^{-3}.

Figure 3 Wavelength dependence of negative photoconductivity in sample N1 for two values of intensity.

Figure 4. Model for negative photoconductivity illustrating the effective reduction in compensation by carrier trapping.

Figure 5 Variation of impurity conduction activation energy ϵ_3 with illumination in sample P2($N_A = 10^{16}$ In atoms cm^{-3}, $N_D = 4 \times 10^{15}$ Sb atoms cm^{-3}).

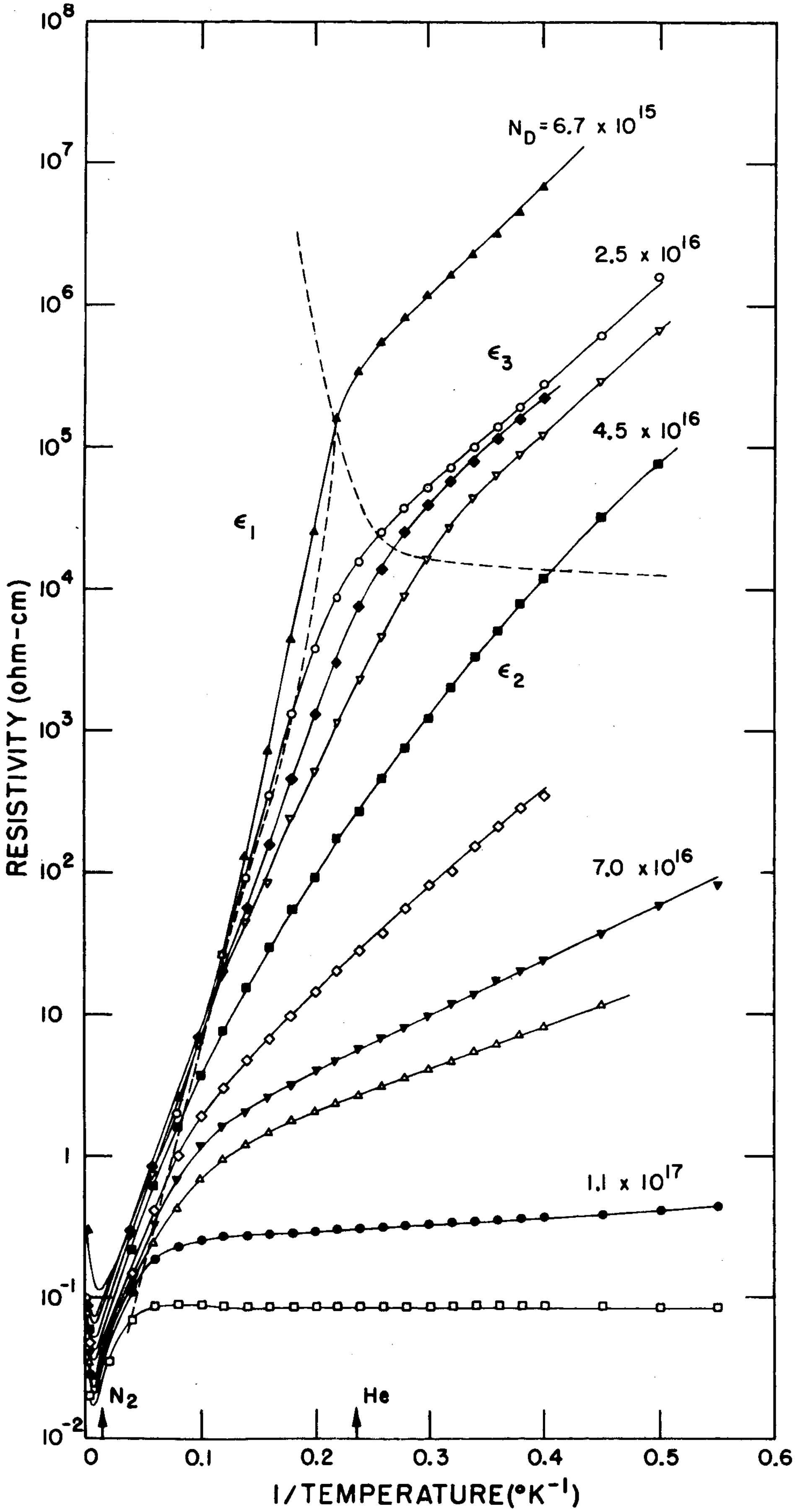
RESISTIVITY (ohm-cm)
1/TEMPERATURE(°K⁻¹)
$N_D = 6.7 \times 10^{15}$
2.5×10^{16}
4.5×10^{16}
7.0×10^{16}
1.1×10^{17}
ϵ_1
ϵ_2
ϵ_3
N_2
He

FIGURE 1

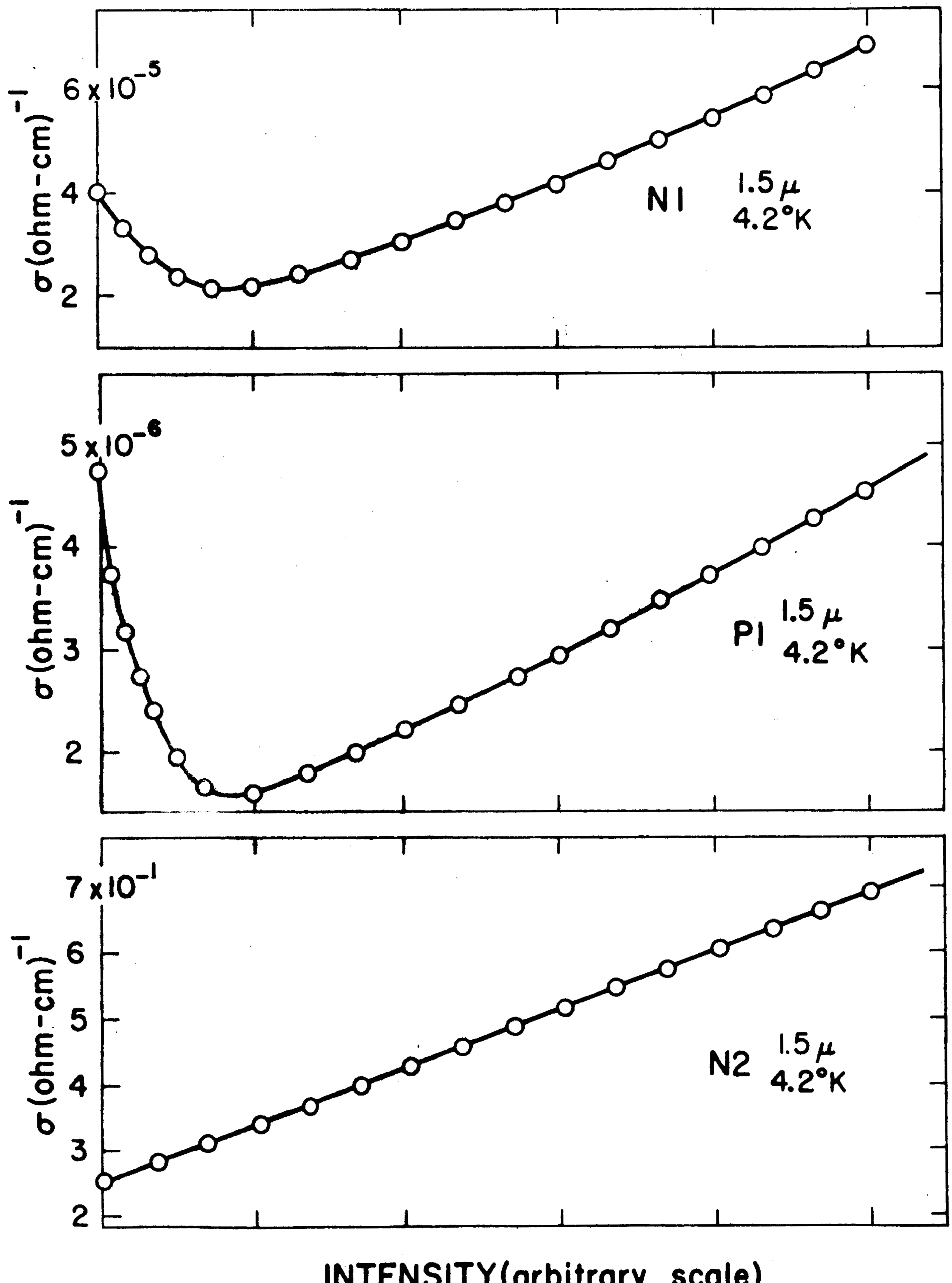
6 x 10^-5
4
2
σ (ohm-cm)^-1
N1 1.5 μ 4.2°K
5 x 10^-6
4
3
2
σ (ohm-cm)^-1
P1 1.5 μ 4.2°K
7 x 10^-1
6
5
4
3
2
σ (ohm-cm)^-1
N2 1.5 μ 4.2°K
INTENSITY (arbitrary scale)

FIGURE 2

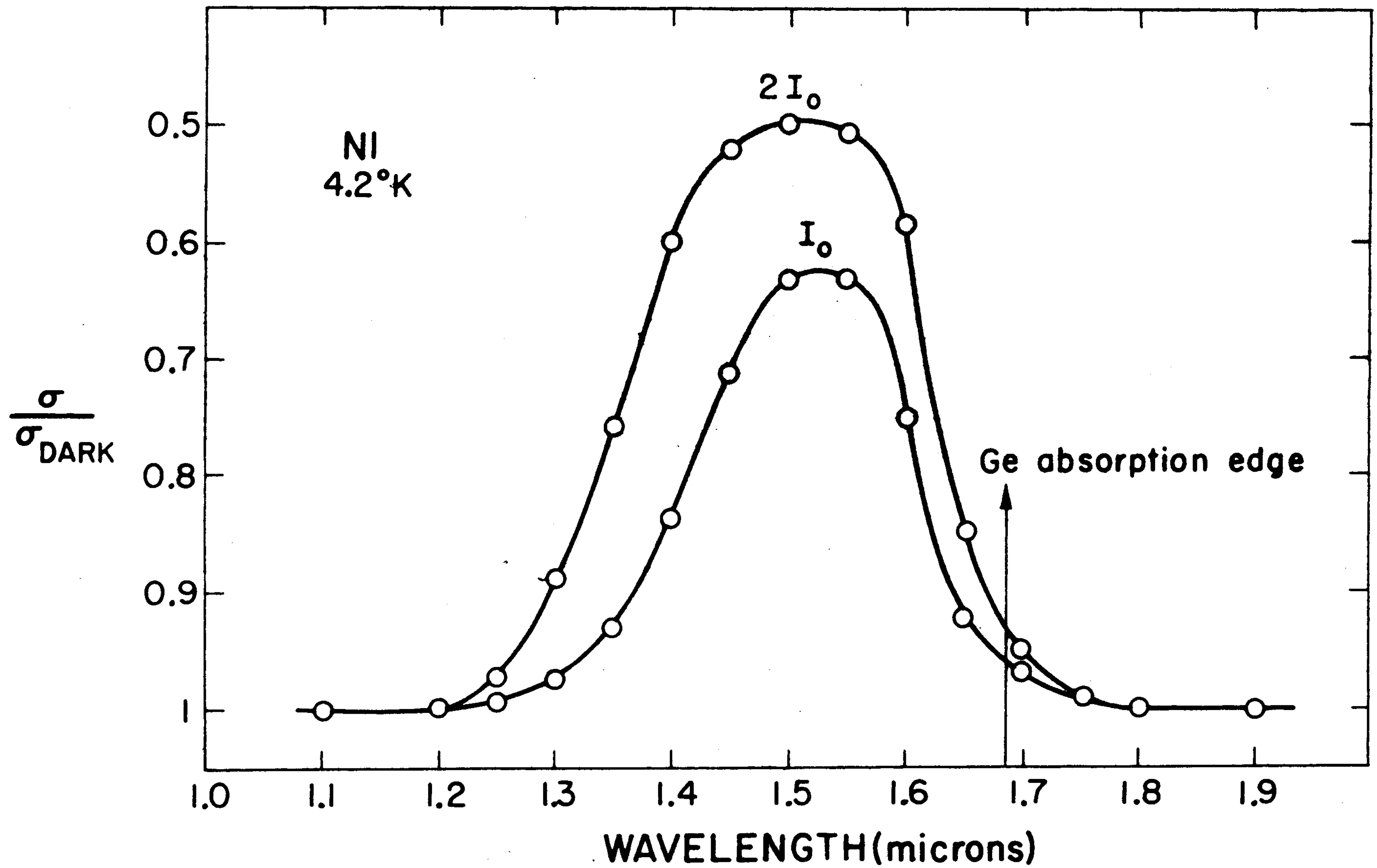
NI
4.2°K
2 I₀
I₀
Ge absorption edge
σ / σ_DARK
0.5
0.6
0.7
0.8
0.9
1
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
WAVELENGTH(microns)

FIGURE 3

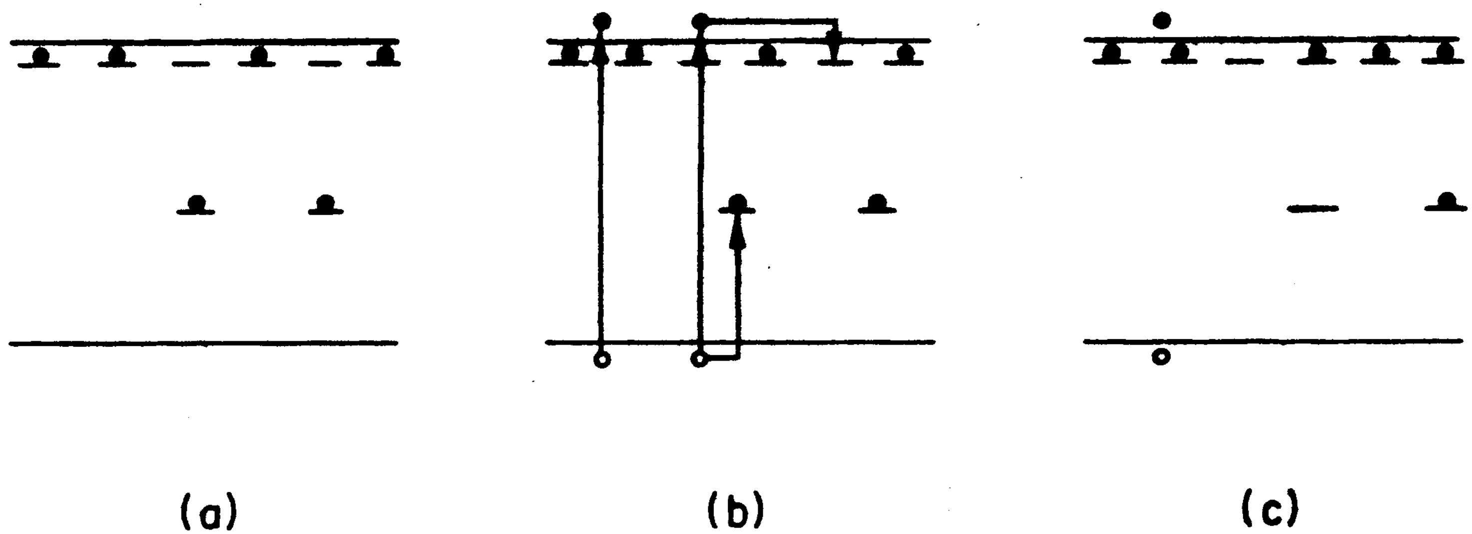

FIGURE 4

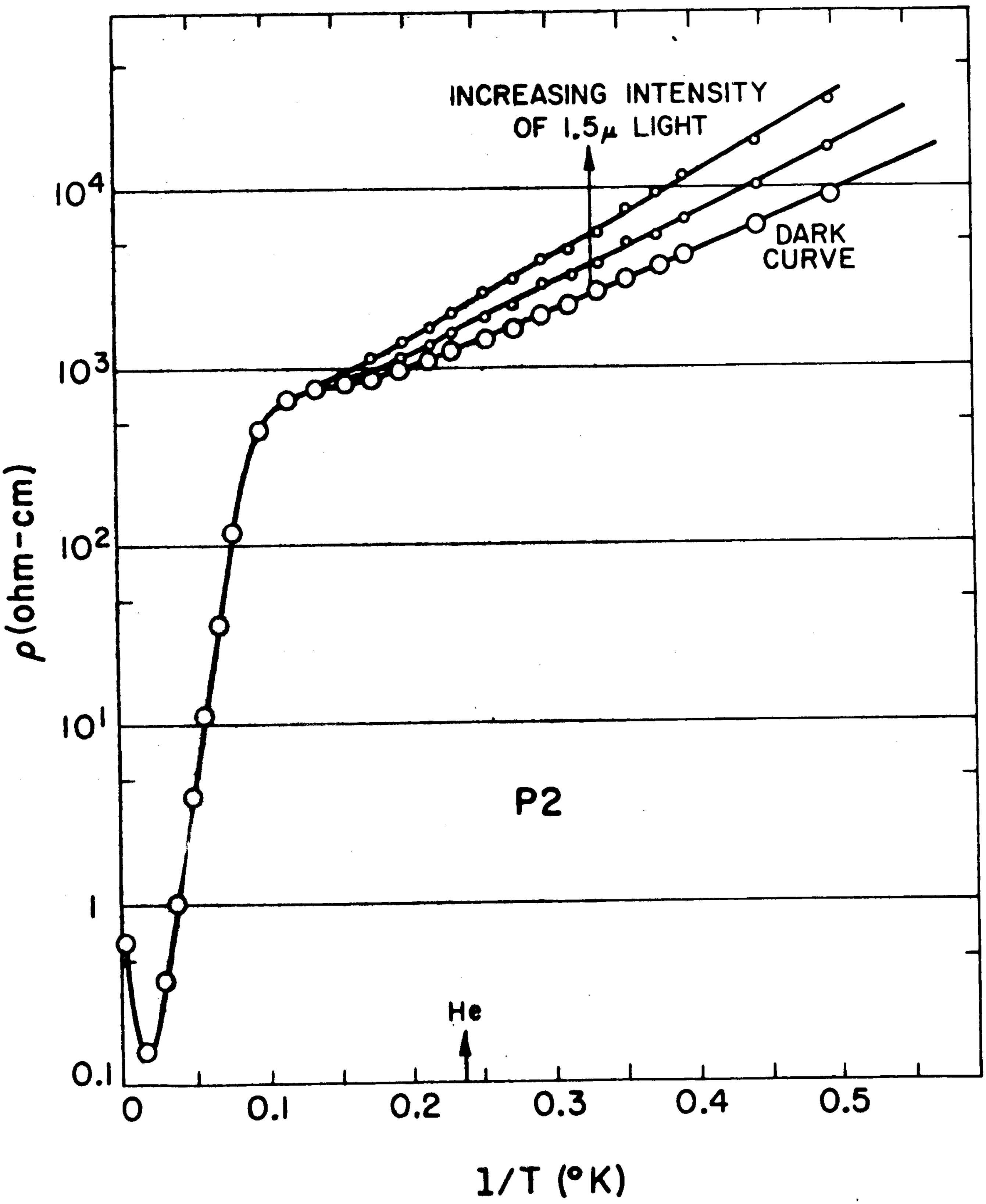
INCREASING INTENSITY
OF 1.5μ LIGHT
DARK
CURVE
P2
He
ρ (ohm-cm)
10^4
10^3
10^2
10^1
1
0.1
0
0.1
0.2
0.3
0.4
0.5
1/T (°K)

FIGURE 5